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29 June 2018

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Zhou, Ye-Ling (2017) 'Flavour symmetric connections with CLFV.', in Proceedings, Prospects in Neutrino Physics (NuPhys2016) : London, UK, December 12-14, 2016. , arXiv:1705.00514.

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NuPhys2016-Zhou
April 17, 2018

Flavour symmetric connections with CLFV

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Flavons are crucial for understanding lepton mixing in models with non-Abelian discrete symmetries. They also result in charged lepton flavour violation (CLFV) via the couplings with leptons. I emphasise that the flavon-triggered CLFV succeeds strong connections with lepton flavour mixing. Relations between branching ratios of CLFV decays and mixing angles are discussed, and CLFV sum rules are obtained. Flavons with masses around hundreds of GeV are consistent by current CLFV measurements.

PRESENTED AT

NuPhys2016, Prospects in Neutrino Physics
Barbican Centre, London, UK, December 12–14, 2016

¹Work supported by ERC Grant NuMass (FP7-IDEAS-ERC ERC-CG 617143)

1 Introduction

Non-Abelian discrete flavour symmetries are directly motivated by large mixing angles measured by neutrino oscillation experiments [1]. Leptonic flavour mixing is explained as the result of the group structure and irreducible representations of the symmetry. One milestone is the realisation of tri-bimaximal (TBM) mixing [2] in A_4 [3, 4]. The TBM mixing predicts $\theta_{12} = 35.3^\circ$ and $\theta_{23} = 45^\circ$, still consistent with current oscillation data in 3σ ranges. However, after observations of a relatively sizable θ_{13} [5], specific modifications to TBM should be considered.

Flavons play a key role in flavour model constructions [6]. They gain vacuum expectation values (VEVs) with special directions and lead to the break of the flavour symmetry. Different residual symmetries may be roughly preserved in different flavon VEVs, and flavour mixing is achieved from their misalignment. The small breaking of the residual symmetries result in deviations of the mixing [7].

Couplings between flavons and leptons not only explain flavour mixing, but also contribute to charged lepton flavour violation (CLFV) [8, 9, 10, 11, 12, 13, 14, 15, 16]. Strongly constrained by flavour symmetries and experimental data, flavon-triggered CLFV shows special properties identified with other new physics contributions [17]. In what follows, I will discuss this phenomenology and its essential connection with flavour symmetries. For definiteness, the flavour symmetry is chosen to be A_4 .

2 Basic structures of A_4 flavour models

Without lose of generality, I show how TBM is realized in most A_4 flavour models. Assuming A_4 is a flavour symmetry conserved at some high scale, it is broken when the energy scale decreases, but some residual symmetries are preserved, $Z_3 \subset A_4$ in the charged lepton sector, and $Z_2 \subset A_4$ in the neutrino sector*. The lepton mass matrices are constrained by the residual symmetries. The tri-bimaximal mixing is a result of the mismatch between the two residual symmetries. These residual symmetries are not precisely preserved. The small breaking of the residual symmetries leads to corrections to the flavour mixing, and gives rise to the non-zero θ_{13} and the Dirac CP-violating phase δ .

New scalars called flavons are necessary to be introduced in flavour models. They gain VEVs with special directions, driving non-trivial lepton mass structures and further realizing flavour mixing. In the simplest case, we need at least two A_4 -pseudo-triplet flavons, φ and χ , one for charged leptons and the other for neutrinos. Combining flavons with leptons and the Higgs, we arrive at effective A_4 -invariant

*Another Z'_2 symmetry, which is not a subset of A_4 , is usually preserved accidentally after A_4 breaking.

operators as follows,

$$\begin{aligned} -\mathcal{L}_l &= \frac{y_e}{\Lambda}(\bar{\ell}_L\varphi)_1 e_R H + \frac{y_\mu}{\Lambda}(\bar{\ell}_L\varphi)_{1''} \mu_R H + \frac{y_\tau}{\Lambda}(\bar{\ell}_L\varphi)_{1'} \tau_R H + \text{h.c.} + \dots, \\ -\mathcal{L}_\nu &= \frac{y_1}{2\Lambda^2}((\bar{\ell}_L\ell_L^c)_{\mathbf{3}_S}\chi)_1 \tilde{H}\tilde{H} + \frac{y_2}{2\Lambda^2}(\bar{\ell}_L\ell_L^c)_1 \eta \tilde{H}\tilde{H} + \text{h.c.} + \dots, \end{aligned} \quad (1)$$

where η is an A_4 -invariant scalar and the dots stand for subleading higher dimensional operators. Once the flavons take VEVs with the following directions

$$\langle\varphi\rangle \propto (1, 0, 0)^T, \quad \langle\chi\rangle \propto (1, 1, 1)^T, \quad (2)$$

in the Altarelli-Feruglio basis [4][†], the charged leptons and neutrinos gain special Yukawa structures, or equivalently, mass structures as

$$Y_l \propto M_l \propto \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}, \quad Y_\nu \propto M_\nu \propto \begin{pmatrix} a+2b & -b & -b \\ -b & 2b & a-b \\ -b & a-b & 2b \end{pmatrix}. \quad (3)$$

And eventually, from them, the TBM mixing is obtained.

To be consistent with data, the residual symmetries should be broken, and corrections to the mixing must be included. Sources for the breaking include

- higher dimensional operators involving different flavons in the Yukawa couplings. For example, VEVs of the 3-dimensional products of χ and φ take this direction $(2, -1, -1)^T$ or $(0, 1, -1)^T$. They break Z_3 or Z_2 , depending on whether they contribute to charged lepton Yukawa coupling or neutrino Yukawa coupling, respectively.
- shifts of the flavon VEVs. That may be resulted from the coupling between different flavons in the potential or interference by other field. The shift of the flavon VEV will not only contribute to lepton Yukawa couplings, but also modify the flavon masses and mixing directly.

These sources may not be independent of each other, and contribute to flavour mixing at the same time.

A very economical approach based on the second source is proposed in Ref. [7]. In this approach, flavon cross couplings between φ and χ break the residual symmetries, shift the VEVs from Eq. (2) to

$$\langle\varphi\rangle \propto (1, \epsilon_\varphi, \epsilon_\varphi^*)^T, \quad \langle\chi\rangle \propto (1 - 2\epsilon_\chi, 1 + \epsilon_\chi, 1 + \epsilon_\chi)^T, \quad (4)$$

[†]The directions of flavon VEVs are not unique, but basis-dependent. A basis transformation $\rho(g) \rightarrow U\rho(g)U^{-1}$ for the triplet representation $\rho(g)$ for $g \in A_4$ will change the VEVs $\langle\varphi\rangle$ and $\langle\chi\rangle$ to $U\langle\varphi\rangle$ and $U\langle\chi\rangle$, respectively. Flavour mixing, which are identified as the misalignment between different VEVs, will not be changed under this basis transformation. The follow-up discussion will be fixed in the Altarelli-Feruglio basis. In this basis, the simplest triplet is a pseudo-real one, with $\varphi_1^* = \varphi_1$, $\varphi_2^* = \varphi_3$, and $\chi_1^* = \chi_1$, $\chi_2^* = \chi_3$ being required.

Here, ϵ_φ and ϵ_χ are small parameters with ϵ_φ being complex and ϵ_χ real. The PMNS matrix is approximately given by $U_{\text{PMNS}} = U_l^\dagger(\epsilon_\varphi)U_{\text{TBM}}U_\nu(\epsilon_\chi)$ with $U_l(\epsilon_\varphi)$ and $U_\nu(\epsilon_\chi)$ representing Z_3 - and Z_2 -breaking effects, characterised by ϵ_φ and ϵ_χ , respectively. Deviations of mixing parameters from those in TBM are expressed as

$$\sin \theta_{13} \approx \sqrt{2}|\text{Im}(\epsilon_\varphi)|, \quad \sin \theta_{12} \approx \frac{1 - 2\text{Re}(\epsilon_\varphi) + 2\epsilon_\chi}{\sqrt{3}}, \quad \sin \theta_{23} \approx \frac{1 + \text{Re}(\epsilon_\varphi)}{\sqrt{2}}, \quad (5)$$

Furthermore, a sum rule between the mixing angle θ_{13} and CP-violating phase,

$$\delta \approx \mp(90^\circ + \sqrt{2}\theta_{13}) \quad (6)$$

for $\text{Im}(\epsilon_\varphi) >, < 0$, respectively, is obtained. I show the numerical results for the correlation between θ_{12} and θ_{23} and the allowed parameter space of $|\epsilon_\varphi|$ vs ϵ_χ in Fig. 1, where 3σ range data of mixing angles in [18] have been used.

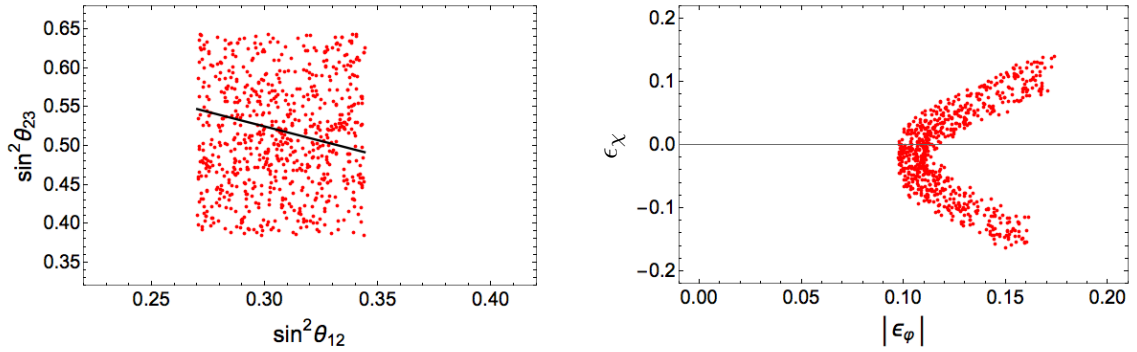


Figure 1: Theoretical prediction of mixing angles (left panel) and the allowed parameter space of $|\epsilon_\varphi|$ vs ϵ_χ (right panel). The straight line corresponds to $\epsilon_\chi = 0$.

3 CLFV induced by flavons

The fact that neutrinos have masses and leptons mix is a convincing evidence of new physics. If there is a mechanism which can explain leptonic flavour mixing, it may also contribute to CLFV since neutrinos and left-handed charged leptons are unified in the electroweak symmetry.

There are already some papers in the literature discussing the connections between CLFV and flavour symmetries. These papers have analysed the following contributions within flavour models. Higher dimensional operators which are not forbidden by A_4 [8]. Contributions of superpartners of leptons or flavons, since most of the flavour models are built in the framework of supersymmetry [8, 11, 15]. Flavons as

$SU(2)_L$ -doublet Higgs [10, 13, 14, 16] and KK modes from warped flavour models [12] have also been discussed in some sense.

I will pay more attention to the essential contribution of the flavour symmetry to CLFV. Here are my guiding principles:

- **Simplicity.** Only SM fields and gauge-invariant flavons will be included. Extra degrees of freedom not essential for explaining flavour mixing will be avoided.
- **Rigour.** Non-trivial properties of the 3-dimensional Altarelli-Feruglio representation of A_4 will be taken care.
- **Consistency with data.** To be consistent with oscillation data, NLO corrections to the mixing will be specified. How these corrections contribute to and connect with CLFV will be analysed carefully.
- **Testability.** Unique features that can distinguish CLFV induced by non-Abelian discrete symmetry from other new physics will be emphasised.

These considerations lead us to the contribution only from the minimal extension of the SM that can explain oscillation data, namely, those flavons and necessary couplings with leptons. As Z_3 is a roughly preserved symmetry in the charged lepton sector, I will classify them into two parts: those consistent with the Z_3 residual symmetry and those contradicting it.

3.1 Z_3 -perserving channels

From the Lagrangian terms in Eq. (1), we can write out the couplings between flavons and charged leptons explicitly as

$$\begin{aligned}\mathcal{L}_l^{\text{eff}} &= \frac{m_e}{v_\varphi} (\overline{e}_L e_R \varphi_1 + \overline{\mu}_L e_R \varphi_2 + \overline{\tau}_L e_R \varphi_2^*) \\ &+ \frac{m_\mu}{v_\varphi} (\overline{\mu}_L \mu_R \varphi_1 + \overline{\tau}_L \mu_R \varphi_2 + \overline{e}_L \mu_R \varphi_2^*) \\ &+ \frac{m_\tau}{v_\varphi} (\overline{\tau}_L \tau_R \varphi_1 + \overline{e}_L \tau_R \varphi_2 + \overline{\mu}_L \tau_R \varphi_2^*) + \text{h.c.} .\end{aligned}\tag{7}$$

The Z_3 symmetry corresponds to the invariance under the transformation

$$\begin{aligned}(e_{L,R}, \varphi_1) &\rightarrow (e_{L,R}, \varphi_1), \\ (\mu_{L,R}, \varphi_2) &\rightarrow \omega^2 (\mu_{L,R}, \varphi_2), \\ (\tau_{L,R}, \varphi_2^*) &\rightarrow \omega (\tau_{L,R}, \varphi_2^*),\end{aligned}\tag{8}$$

where $\omega = e^{i2\pi/3}$. Namely, $e_{L,R}, \varphi_1$ are invariant under the transformation of Z_3 , $\mu_{L,R}, \varphi_2$ are covariant with a Z_3 charge 2, and $\tau_{L,R}$ are covariant with a Z_3 charge

1. While the Z_3 -invariant flavon φ_1 induces flavour-conserving processes, the Z_3 -covariant flavon φ_2 is the main source of CLFV. As e , μ and τ take different Z_3 charges, it is easy to prove that the only allowed processes are $\tau^- \rightarrow \mu^+ e^- e^-$ and $\tau^- \rightarrow e^+ \mu^- \mu^-$. The other 3-body decay and all radiative decay modes are forbidden by the Z_3 symmetry [9].

In the case of transfer momentum much lower than the scale of flavour symmetry and flavon masses, one can integrate out φ_1 and φ_2 , and derive the effective 4-fermion interactions. Those for $\tau^- \rightarrow \mu^+ e^- e^-$ and $\tau^- \rightarrow e^+ \mu^- \mu^-$ can be expressed as

$$\frac{m_\mu m_\tau}{v_\varphi^2 m_{\varphi_2}^2} (\bar{e}_L \mu_R) (\bar{e}_L \tau_R), \quad \frac{m_\mu m_\tau}{v_\varphi^2 m_{\varphi_2}^2} (\bar{\mu}_R e_L) (\bar{\mu}_L \tau_R), \quad (9)$$

respectively. The coefficients are the same, from which we get approximatively equal branching ratios of these two processes

$$\text{Br}(\tau^- \rightarrow \mu^+ e^- e^-) \approx \text{Br}(\tau^- \rightarrow e^+ \mu^- \mu^-), \quad (10)$$

both suppressed by $\left(\frac{m_\mu m_\tau v^2}{m_{\varphi_2}^2 v_\varphi^2}\right)^2$. Assuming flavon VEV and flavon mass around the electroweak scale, the branching ratios are still two orders of magnitude below current experimental upper limit [17].

3.2 Z_3 -breaking channels

Then we consider Z_3 -breaking CLFV channels. Since the Z_3 -breaking effect can give rise to non-zero θ_{13} and possible deviations of the other mixing parameters from their leading results, this effect should also be included in the discussion of CLFV. As there may be different Z_3 -breaking origins, it is hard to do a generic analysis for the Z_3 -breaking CLFV processes. To simplify the discussion, I will consider, as in [17], the Z_3 -breaking from only flavon cross couplings.

The breaking of Z_3 contributing to CLFV can be distinguished into three parts:

- the mixing of left-handed charged leptons e_L , μ_L and τ_L , i.e., $U_l(\epsilon_\varphi)^\dagger$.
- the mixing between Z_3 -invariant flavon φ_1 and Z_3 -covariant one φ_2 .
- the mass splitting between the two real degrees of freedom of φ_2 .

We put these contributions into CLFV 3-body and radiative decay processes, and find all these decay modes are allowed. Compared with the Z_3 -preserving processes, they are further suppressed by the additional parameter ϵ_φ .

[‡]There is also a small mixing of right-handed charged leptons e_R , μ_R and τ_R . it is suppressed by both ϵ_φ and the hierarchy of charged lepton masses due to arrangements of these particles as singlets in A_4 , i.e., $e_R, \mu_R, \tau_R \sim \mathbf{1}, \mathbf{1}', \mathbf{1}''$.

For the 3-body decay processes, branching ratio sum rules of τ decays are observed:

$$2(B_{\mu^+\mu^-e^-} - 2B_{\mu^+\mu^-\mu^-})^2 + (5B_{e^+e^-\mu^-} + 10B_{\mu^+\mu^-\mu^-} - 6B_{\mu^+\mu^-e^-})B_{e^+e^-\mu^-} = 0, \\ B_{e^+e^-\mu^-} \approx 8|\epsilon_\varphi|^2 \text{Br}(\tau^- \rightarrow \mu^+e^-e^-). \quad (11)$$

Here, $B_{\mu^+\mu^-e^-}$, $B_{\mu^+\mu^-\mu^-}$, $B_{e^+e^-\mu^-}$ are branching ratios of $\tau^- \rightarrow \mu^+\mu^-e^-$, $\tau^- \rightarrow \mu^+\mu^-\mu^-$ and $\tau^- \rightarrow e^+e^-\mu^-$, respectively. In the limit $m_{\varphi_1} \ll m_{\varphi_2}$, we get $B_{\mu^+\mu^-e^-} \approx 2B_{\mu^+\mu^-\mu^-} \gg B_{e^+e^-\mu^-}$, and on the contrary, we obtain $B_{\mu^+\mu^-e^-} \approx 4B_{\mu^+\mu^-\mu^-} \approx 2B_{e^+e^-\mu^-}$. These processes are weaker than the Z_3 -preserving processes because of the ϵ_φ suppression. For $\tau^- \rightarrow e^+e^-e^-$ and $\mu^- \rightarrow e^+e^-e^-$, their branching ratios are suppressed by electron mass, thus, far away from experimental limit.

Radiative decays are also allowed by cross couplings. $\tau^- \rightarrow \mu^- \gamma$ and $\tau^- \rightarrow e^- \gamma$ are induced by the mixing between charged lepton flavour eigenstates and by the mixing between φ_1 and φ_2 . The approximately equal branching ratios are predicted,

$$\text{Br}(\tau^- \rightarrow e^- \gamma) \approx \text{Br}(\tau^- \rightarrow \mu^- \gamma). \quad (12)$$

Assuming the flavon VEV and masses above the electroweak scale, these branching ratios $\lesssim 10^{-11}$, 3 orders of magnitude below the current best experimental limits.

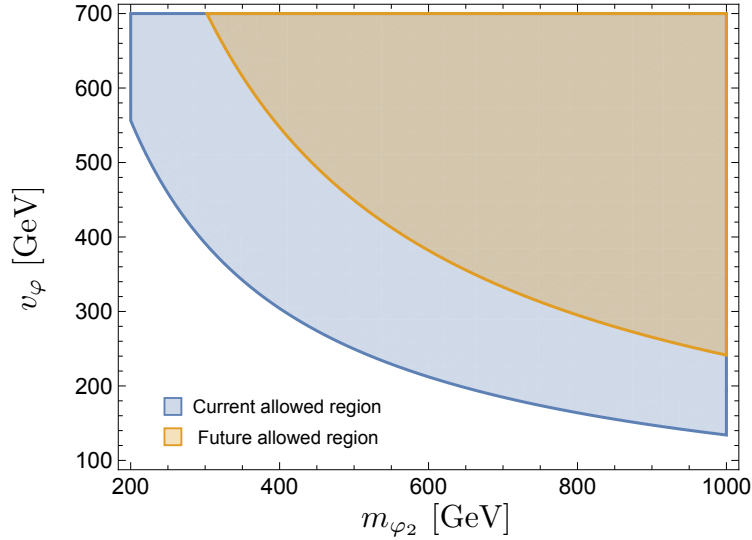


Figure 2: Flavon VEV and φ_2 mass constrained by $\mu^- \rightarrow e^- \gamma$ experiments. $|\epsilon_\varphi|$ is fixed at 0.1 for generating θ_{13} . The current (MEG) and future (MEG II) constraints are set to be $\text{Br}(\mu^- \rightarrow e^- \gamma) < 4.2 \times 10^{-13}$ and 4×10^{-14} , respectively.

The most stringent constraint is from $\mu^- \rightarrow e^- \gamma$. It is induced by the mixing of charged leptons and the mass splitting of the two real degrees of freedom of the

complex flavon φ_2 . This process is suppressed by ϵ_φ and m_μ , but it has been measured more precisely than the τ decay. Regions of v_φ and m_{φ_2} allowed by current experiments and testable at the near future experiments are shown in Fig. 2. The current upper limit is given by the MEG experiment, around 4.2×10^{-13} (90% CL) [19]. By fixing the flavon VEV at the electroweak scale, we obtain the lower limit of the φ_2 mass is around 500 GeV. In the future, MEG II will push the upper limit of the branching ratio to 4×10^{-14} [20]. This experiment will have the potential to exclude a large parameter space.

4 Conclusion

Flavour symmetries are usually treated as the origin of leptonic flavour mixing. The newly introduced interactions in flavour models will not only generate flavour structure in lepton mass matrices, but also contribute to CLFV processes. The flavon-triggered CLFV has strong connections with the symmetries.

In A_4 models, all CLFV processes can be classified by the residual symmetry Z_3 . The only allowed Z_3 -preserving processes are $\tau^- \rightarrow \mu^+ e^- e^-$, $\tau^- \rightarrow e^+ \mu^- \mu^-$ and their conjugate processes. All the other 3-body and radiative decays are Z_3 -breaking. Several CLFV sum rules are obtained. This is a highlighted feature to connect non-Abelian discrete flavour symmetries with CLFV. While the Z_3 -preserving processes are suppressed by charged lepton masses, the Z_3 -breaking processes are further suppressed due to the consistency with oscillation data. The current experimental constraints are loose. Hundreds of GeV scale flavon VEV and mass are still allowed.

ACKNOWLEDGEMENTS

I am grateful to the NuPhys 2016 organizers for their kind invitation.

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